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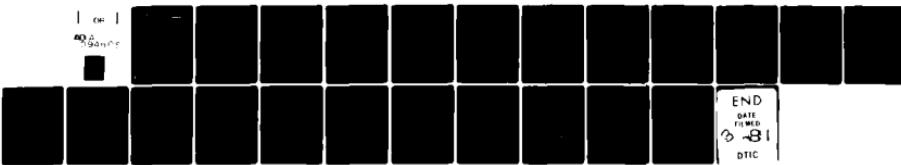
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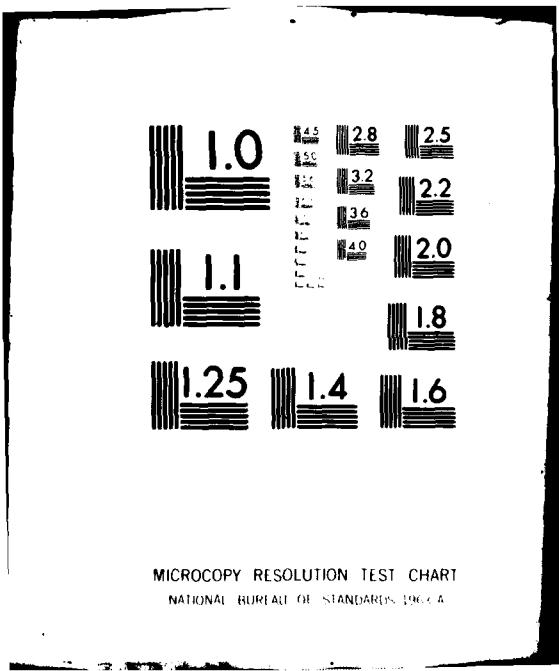
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DETECTION OF MOTION UNDER TARGET UNCERTAINTY
AND PERIPHERAL PRESENTATION

Robert Sekuler



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) We have developed a model to account for the loss in visibility of moving targets that occurs when an observer is uncertain about the target's direction of motion. The model's key features are an array of directionally selective visual mechanisms and a rule governing the mechanisms from which an observer will derive sensory data. In response to uncertainty about two possible directions of motion, the observer is assumed to use a mechanism whose peak sen-		

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sitivity is to a direction midway between the two possible directions. Seven experiments, using both reaction time and forced-choice data, demonstrate the predictive advantages of this midway model over competing single-band and multiple-band models. Additionally, the experiments reveal several new properties of human motion perception: (a) Direction and velocity information have orthogonal representations in the visual system; (b) although motion sensitivity does not vary with direction, the precision with which small changes in direction can be recognized does, reflecting differential breadth of tuning for directionally selective mechanisms sensitivity to various directions; and (c) motion-analyzing mechanisms are broadly tuned for direction as well as speed.

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For some time we have known that the ability to see and appreciate the characteristics of moving targets depends upon an interesting class of visual mechanisms designed especially for this job. Human psychophysics has provided much detail about them with data converging from a variety of paradigms, including selective adaptation (Sekuler & Ganz, 1963), sub-threshold summation (Levinson & Sekuler, 1975), aftereffects (Keck, Pallela, & Pantle, 1976), and masking (Ball & Sekuler, 1979). In general, these studies, and others, tell us how much information is potentially available in motion-sensitive visual elements. As you might expect, this potential will be one of our concerns in this paper.

But we will have to go well beyond the realm of potential information if we are to bridge the gap between laboratory studies of motion perception and the use to which we put motion perception everyday, outside the laboratory. Since the Seminar is particularly concerned with this gap, we shall spend some time considering the issue.

But first let us establish a foundation for what is to come. Since one of us recently prepared two extensive treatments of psychophysical approaches to motion perception (Sekuler, 1975; Sekuler, Pantle & Levinson, 1978), we shall spare you a repeat of that material. Instead, we shall summarize briefly one or two highlights of those reviews and go on to emphasize insights that postdate the earlier reviews.

Here is the plan we shall follow in this paper. First, we shall describe the stimuli and general methods used in the experimental work to be considered. Then we shall outline the model that informs our work on motion perception. Next will come a consideration of the model's details, particularly as they bear upon the character of visual mechanisms that enable us to see moving targets. The concluding section of the paper will take us further from the laboratory, to the consequences for motion perception of an observer's inability to predict precisely what moving target he is looking for. This sort of effect, called stimulus uncertainty, has occupied a good deal of our time in the past three years and has taught us much about motion perception and about perception more generally. In the brief treatment of stimulus uncertainty here, we will consider three separate but complementary topics: performance losses associated with stimulus uncertainty, how those losses can be compensated for or mitigated, and the discrepancy between being able to see a moving target and being able to identify its direction of motion.

Stimuli and Dependent Measures

The stimuli used in all the work we shall discuss were patterns of isotropic, random dot patterns presented as luminance increments on a cathode ray tube (CRT). The spatial, temporal and intensive properties of the dot patterns were controlled in real time by a small laboratory computer. Their isotropy means that the dot patterns had equal energy along all axes. This property is important since we wished to study responses to movement in as pure a form as possible, without the complications that would be introduced by the presence of oriented contours. The isotropy of our patterns was assessed in

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two ways: by numerical two-dimensional Fourier analysis and by visual inspection of the pattern's optical transform (Lipson, 1973).

Typically, the CRT on which dot patterns were displayed was illuminated by a constant veiling light of slightly less than 2 cd/m². In some studies, the incremental luminance of the dot patterns was an independent variable; in others it was fixed at one suprathreshold level, usually a level 50 times detection threshold. Observers sat with heads supported in a chin rest some 57 cm from the CRT. Viewing was usually binocular (we shall indicate when we come to the two exceptions to this rule). In addition, the CRT was most often masked with a circular aperture of 8 degrees diameter. In any one frame of the display (33 msec), the computer plotted 512 dots on the CRT; typically, slightly more than 400 dots were visible within the 8 degree aperture at any one time.

The dots within a pattern moved along parallel tracks. Put another way, as the dot patterns moved, dots remained in the same relative spatial phases with respect to one another. Opposite sides of the display were functionally connected so that a dot moving off one side would reappear a moment later on the opposite side. This connection gave the display the appearance of an infinite, textured surface moving continuously behind the aperture.

Our experiments have made use of several different indicator responses and trial structures. This variety of approaches is necessary to obtain the converging operations that we must have to be sure any particular description of motion sensitivity is not simply a singular outcome of one method.

We shall outline three of the major procedures we have used: reaction time (RT) to motion onset, two-alternative forced choice (2-AFC) detection of motion and a rating-scale procedure derived from signal detection theory. This last method allows us to measure an observer's bias as well as his sensitivity to motion.

RT to Motion Onset. In this procedure, the incremental luminance of the dot patterns was adjusted to make them easily visible. Thus we were not concerned with detectability in the usual sense. On each trial dot patterns appeared first as a stationary pattern. Then, after a random foreperiod ranging from 2 to 3.5 seconds, the dot patterns began moving without warning to the observer.

The observer pressed a switch as soon as he detected the initiation of the movement. It is important to emphasize that the observer did not have to judge the properties of the movement, e.g. direction or speed. He only had to press a key at motion onset. As soon as the key was pressed the pattern disappeared and the CRT remained blank until the next trial. The dependent measure was the time between motion onset and the observer's key press (i.e., the RT).

2-AFC Testing. Each trial consisted of two, 600 msec intervals, defined by co-extensive, high pitched tones. During one interval the CRT was blank; during the other moving dot patterns were presented on the CRT. The interval, first or second, containing the moving dot patterns varied randomly from one trial to the

next. The observer's task was to identify the interval containing motion. The dependent measure is the percent of correct identifications. Usually, we converted percent correct to a corresponding d' value. The rationale was that although percent correct is not linearly related to an observer's sensitivity, d' is.

Rating-Scale Method. This was a variant of the yes-no rating scale procedure used in signal detection work (McNicol, 1972). Each trial was defined by a high pitched tone. On half the trials the CRT was blank; on remaining trials moving dot patterns were presented. After each trial, the observer used a rating scale (the numbers from 1-6) to describe his judgment about whether or not motion had been presented and his confidence in that judgment.

These ratings are conditionalized upon their stimuli, cumulated and converted using standard procedures into two non-parametric statistics: $P(A)$, a measure of sensitivity, and B , a measure of the observer's criterion. $P(A)$ is the decimal fraction of the unit square's area that lies below the receiver operating characteristic. B is analogous to "beta" in parametric treatments of signal detection. We transform $P(A)$ to $zP(A)$ to obtain a measure linear with sensitivity or d' . The availability of the dual measures allows us to separate sensitivity changes from those associated with criterion or motivation.

Elements of a Model

Our main theoretical concern is with mechanisms that can be described as "directionally-selective". These mechanisms can be treated as filters, attenuating some input signals more strongly than others. The input signals we have in mind are stimuli moving in one direction or another. As with other filters, a directionally-selective mechanism can be characterized in terms of its optimum input (here, its center direction) and the rate at which its response changes as inputs diverge from that optimum input. This rate of change in response is usually referred to as sharpness of tuning.

Figure 1 shows a set of directionally-selective mechanisms arrayed along the direction continuum. For convenience we have given the mechanisms triangular sensitivity profiles --though much of the model's behavior would be unaltered by substituting other functions that decline symmetrically and monotonically with distance from the center direction. We have settled on functions that are symmetric and monotonically declining because of selective-adaptation experiments with random dot patterns. Levinson and Sekuler (1980) used that procedure to produce a two-dimensional picture of selectivity for direction of motion. After observers adapted to a pattern of dot patterns moving in one direction, the luminance detection threshold for patterns of test dot patterns moving in the same or similar directions was elevated. As adapting and test directions diverged, threshold elevation produced by the adapting pattern decreased.

The "tuning curves" for directional selectivity measured by this technique were rather broad. In fact, some elevation is present even when test and adapting directions differ by 45 degrees. By the time the directions differ by 70 degrees or so, their interactions have dropped to zero. We wish to emphasize

that these effects are *directional*, not axial in character. First, there is no threshold elevation --nor facilitation, for that matter-- when test and adapting directions differ by 180 degrees. Second, the tuning disappears when observers use an alternative criterion, one related to the detection of pattern rather than motion *per se*. Further details are provided in Levinson and Sekuler (1980).

Other data, too, demonstrate that the tuning curves of directionally-selective mechanisms are symmetric and monotonic. Here we shall consider only one such demonstration, derived from the noise masking experiments of Ball and Sekuler (1979). They required observers to detect moving dot patterns following exposure to noise containing various directional components. Here, two main types of noise are of interest. One kind can be characterized as "broadband" --the noise contained equal amounts of all directions of motion (consider the analogy to white noise). The other kind was noise from which certain bands of directions had been digitally filtered. Varying the band of noise filtered from the noise, Ball and Sekuler examined how various direction bands affected the detection of some test direction.

Consider the rationale for this approach. Suppose that the detection of some test direction depended upon the response of a particular directionally-selective mechanism. Depending upon its directional content, the masking stimulus could inject noise into the filter whose response signals the presence of the test direction. As would be true for any real system, with temporal impulse response of greater than zero duration, the effect of the visual noise would outlast the masking stimulus, lowering the effective signal/noise ratio produced by the subsequently presented dot patterns moving in one direction.

The dependent measure was RT to the onset of unidirectional motion immediately following the masking noise. Since the masking noise was of variable duration (akin to a random foreperiod in the usual RT experiment) the observer could not divine --without actually *seeing* the unidirectional test motion-- when the motion would occur. In this way, RT to motion onset could be used as an index of the visibility of the motion.

For any one test direction, RT is elevated by those components of noise that are most nearly in the same direction as the test. When those similar components are filtered out of the noise, the noise is unable to elevate RT. As components are filtered out, RT declines symmetrically and monotonically with respect to the test direction. Again, the tuning is broad; noise components as different from the test direction as 45 degrees significantly elevate RT to the test direction but the effect of noise components 70 degrees from the test direction is virtually nil.

Returning to Figure 1, consider another feature of the directionally-selective mechanisms portrayed there. The magnitude of response evoked in any mechanism by motion of constant speed and contrast is represented by the *height* of the tuning function at the point on the direction continuum that corresponds to the stimulus direction of interest. Note that all mechanisms are shown with the same sensitivity at their center

directions. The assumption of equal peak sensitivities derives from several demonstrations that sensitivity to moving targets is independent of their direction of motion. Let us briefly consider the evidence for this assumption.

Recent work has provided three separate demonstrations relevant to this question. First, Ball and Sekuler (1980) obtained RTs to the movement of dot patterns in various directions. These RTs, measured in the absence of masking noise, were invariant with direction. Second, Levinson and Sekuler (1980) measured contrast thresholds for moving dot patterns these, too, were independent of direction. Finally, Marshak (1980) measured the duration of motion after-effects (Waterfall Illusion) produced by exposure to dot patterns moving in various directions and found that after-effect duration was constant for all directions tested. The results of all three studies are summarized in Figure 2: using three different measures of response to motion all demonstrate that sensitivity to motion does not vary with direction. Hence, all the tuning functions in Figure 1 should have the same height.

Returning once again to Figure 1, note that the directionally-selective mechanisms are represented as having uniform breadth of tuning. While this may be nearly correct within restricted regions of the direction continuum, it most certainly is not correct if one tries to describe the entire continuum. There are several converging demonstrations that tuning varies with center direction. The ones we shall discuss compare tuning about an oblique direction (45 degrees) to tuning about a direction along a major axis (90 degrees). Let us consider each of these demonstrations in turn.

Using the noise masking paradigm mentioned earlier, Ball and Sekuler (1980) found that tuning functions were broader when the test direction was 45 degrees than when it was 90 degrees. Within the logic of their approach, this difference implies that the directionally-selective mechanism responsible for detecting upward motion (90 degrees) is more narrowly tuned than the comparable mechanism responsible for detecting motion in an oblique direction. Since their original dependent measure was RT to motion onset, Ball and Sekuler wanted to verify the conclusion using a procedure more directly related to tuning in a conventional sense. They reasoned that these differences in tuning should also show up in a differential ability to detect changes in direction of motion around 90 degrees and changes in direction around 45 degrees.

As a test, they used the method of constant stimuli to measure direction difference thresholds with two different standard directions, 90 and 45 degrees. Each trial consisted of two intervals, 600 msec long, separated by an interval of one second. The first interval contained motion in the standard direction; the second interval contained motion in a comparison direction --either the same as the standard, 1 degree or 2 degrees clockwise or counterclockwise relative to the standard. The observer judged the direction of movement in the second interval relative to that in the first. Difference thresholds were obtained from the least squares fits to the psychometric functions. The difference threshold for upward motion was 3.45

degrees and that for oblique motion was 8.42 degrees. A similar result has been obtained by Machamer (unpublished) as part of a study of direction difference thresholds for dot patterns moving at several speeds and in various directions. She, too, found the difference threshold for 90 degrees to be about-half that for 45 degrees.

These results with difference thresholds are consistent with differential tuning for mechanisms sensitive to oblique and upward motion. The following formalizes the necessary argument. Consider a stimulus of direction appropriate to produce a maximal response from one mechanism in Figure 1 (the mechanism's center direction). The response of the mechanism is characterizable by the product of a) the intensity of the stimulus and b) the sensitivity of the mechanism to that stimulus. Obviously, if the direction of the stimulus changes, the mechanism's response will decrease. Assume that a just noticeable change in direction requires a criterion change in the mechanism's response. A broadly tuned mechanism will yield that criterion change only after a larger stimulus change than would be required to produce the same criterion change in a more sharply tuned mechanism.

Extensions to the Simpig Model

The model just sketched fails to provide all the detail we would like about motion perception, even in the simplest situations. For example, target speed is ignored. One justification for this particular omission is that speed and direction may well be probably coded independently by human visual mechanisms (Ball & Sekuler, 1980). But both psychophysics and physiology suggest that the neural coding of target velocity presents an intriguing problem all by itself. Obviously, no model of motion perception can claim completeness if it ignored the problem of perceived speed. At various levels of the mammalian visual system, the receptive fields of cells that respond to moderate and high rates of temporal modulation tend to be more uniformly distributed across the visual field than are those of cells that are less responsive to such temporal modulation (Fukuda and Stone, 1974; Kirk, Levick and Cleland, 1976). This difference between retinotopic distributions led Tynan and Sekuler (submitted) to seek corresponding differences in retinotopic distribution of psychophysical responses.

They wondered whether the distributions of receptive fields of cells responsive to different rates of temporal modulation might affect psychophysical responses to moving targets at various eccentricities. This led them to examine two dependent variables at various retinal eccentricities. Based on the physiological data above, their hypothesis was that, with sufficiently high target speeds (and correspondingly high rates of temporal modulation) psychophysical responses would be invariant with eccentricity.

In their first experiment, Tynan and Sekuler measured RT to motion onset for upward moving dot patterns presented at various eccentricities. The screen of the CRT was masked by a 10 degree diameter circular aperture. An electronic blanking circuit eliminated dot patterns from either the center of the screen or from its periphery. As a result, the circuit produced

either a patch of dot patterns in the middle of the screen, or a central area devoid of dot patterns surrounded by an annulus of dot patterns. With either central patch or annulus, dots moving into the blanked zone disappeared; dots leaving the blanked zone reappeared.

Annuli were either 0, 2, 4, 6 or 8 degrees in inner diameter; central stimulus patches were either 2, 4, 6, 8 or 10 degrees in diameter. RTs were measured to stimulus velocities of 0.25, 1, 4, and 16 deg/sec. The main results of this experiment are shown in Figure 3. With annular stimuli (left panel), the lowest velocity, 0.25 deg/sec, yielded RTs that increased steadily with annulus size. At higher velocities, RT was independent of annulus size. With central patches of moving dot patterns (right panel), patch size influenced RT only between a 2 degree patch and one of 4 degrees at the lowest speed used. For all higher velocities, RTs were invariant with patch size. Note, in addition, that in both panels, RT declines with increasing stimulus velocity.

Visual functions that depend upon spatial resolution--acuity and, very likely, RT to very slow movement--fall off dramatically over the portion of the field studied in this experiment (LeGrand, 1957). We believe that such visual functions depend upon physiological mechanisms that respond preferentially to lower temporal frequencies. The rapid decline in psychophysical spatial resolution is consistent with the hypothesis that cells responsive to lower temporal frequencies are more likely to have receptive fields in the center of vision. RTs to moderate speeds of motion show no decline over this same range of eccentricities. Very likely, cells with appreciable sensitivity to higher rates of temporal modulation participate in the detection of such motion. The invariance in RT with eccentricity is consistent with the hypothesis that cells with receptive fields in the periphery respond to higher temporal rates.

In a second, related experiment, Tynan and Sekuler measured the perceived speed of targets at various eccentricities. These measurements were made for targets covering a range of speeds. Stimuli were random dot patterns moving upward within a strip 28 degrees high by 4.7 degrees wide. Observers matched the apparent speed of a target at each several eccentricities with the adjustable speed of similar dot patterns presented in the center of vision. Test targets could be presented immediately to the left of the fixation point, or at various distances from it: 7.5, 15, 22.5, and 30 degrees. The duration of any movement varied randomly between 1.5 and 2.5 seconds, making it impossible to judge velocity simply from the distance traveled by any particular element in the pattern. Target velocities of 0.25, 1, 4, and 16 deg/sec were factorially combined with the five eccentricities.

Figure 4 shows the mean velocity matches to dot patterns moving at 0.25, 1, 4, and 16 deg/sec. Note that no data are given for the 0.25 deg/sec stimulus at eccentricities beyond 7.5 degrees. These data have been omitted because on more than half the trials with such eccentricities, the 0.25 deg/sec stimulus appeared stationary, a phenomenon reported by Lichtenstein some

years ago (1963). Values plotted against the ordinate have been normalized by dividing each by the actual speed of the test pattern. Plotted in this way, ordinate values less than unity indicate the eccentric target appeared to move more slowly than it would have with central viewing. The results experiments can be summarized simply: eccentrically-viewed dot patterns appear to move more slowly than do centrally-viewed ones. This slowing effect increases with eccentricity and decreases with target speed.

In both these experiments, psychophysical responses to slowly moving targets change rapidly as a function of eccentricity of presentation. Also, in both cases, psychophysical responses to rapidly moving targets are nearly invariant with eccentricity of presentation. These experiments sought to test an hypothesis about psychophysical parallels to the retinotopic distributions of neural cells whose temporal responses differ from one another. The effects obtained seem to parallel the retinotopic distributions of neural cells that respond best to low rates of temporal modulation and of neural cells that respond best to higher rates of modulation.

Obviously, there needs to be to a follow-up with other kinds of temporally modulated stimuli at various eccentricities. Such stimuli should include spatially localized targets whose eccentricity can be specified more precisely.

But, follow-ups aside, the work just described does offer an important lesson that others should consider. Although many psychophysical theorists have found it convenient to dichotomize visual mechanisms into "sustained" and "transient", the visual system very likely does not itself always respect this bipartite classification. But it is easy to see how one could be misled into believing such a dichotomy characterized the structure. For example, if Tynan and Sekuler had considered only extreme speeds, there would have been a clear difference in visual response as a function of eccentricity. This clear separation simulated a dichotomy. However, if we also take account of intermediate speeds, responses define a continuum between these extremes. For such intermediate velocities, psychophysical responses are neither invariant with eccentricity nor do they exhibit as rapid a decline as do responses to the most slowly moving targets. As we have been so well reminded by Kelly (1977), stimuli for many visual responses must be defined on a continuum of both spatial and temporal dimensions.

Studies of Stimulus Uncertainty

When an observer cannot anticipate precisely the characteristics of a moving target that he has to detect, the visibility of that target is drastically reduced (Sekuler & Ball, 1977). Outside the laboratory, the vast bulk of our responses to moving targets come in face of such uncertainty. But what is the effect of not knowing precisely the sort of moving target one is looking for? In the laboratory, and presumably outside as well, inability to anticipate a target's precise speed or its direction of motion produces a substantial performance loss. Such losses in detectability have been demonstrated using a variety of psychophysical procedures, including criterion-free ones. Since our group at Northwestern

has published extensively on the effects of uncertainty, we will not repeat those findings here. Instead, let us describe some new work on certain aspects of direction uncertainty that may illuminate motion perception in general.

The first experiment is one of a series dealing with the amelioration of performance losses from uncertainty. The strategy used by Ball and Sekuler (unpublished) was to provide cues to the observer that told him with varying degrees of reliability what direction he would have to detect. They asked how reliable the cue had to be in order to diminish the effect of direction uncertainty. For example, did the cue have to be exactly right in order to help the observer? To answer the question, three types of blocks of trials were run. In blocks of ~~Certainty~~ trials, all movement was in the same direction. Thus, there no direction uncertainty. In blocks of ~~Cueless~~-Uncertainty, the direction in which the dot pattern moved was drawn randomly from a uniform distribution covering all 360 degrees and no cue was provided. In blocks of ~~Cueless~~-Uncertainty, an oriented line appeared 700 msec before the onset of motion to provide the observer an cue as to direction of motion that would occur. Each trial consisted of a warning signal, the cue (oriented line on for 50 msec), the 700 msec delay, and finally the observation interval of 500 msec.

Seven different levels of cue reliability were run (360, 300, 240, 180, 120, 60, and 0 degrees). To understand the meaning of cue reliability, consider three examples. In the 360 degree condition the cue orientation was perfectly unreliable; regardless of the cue orientation, subsequent movement could be in any direction. In the 180 degree condition, stimulus movement following the cue was randomly chosen from a uniform distribution within 180 degrees of the indicated direction. Thus the motion could vary by 90 degrees either side of the direction indicated by the cue. In the 0 degree condition, the direction of movement was identical to that indicated by the cue. This condition provides a perfectly reliable cue. Movement was presented on half of the 30 trials per block. On the other half, the CRT was illuminated only by the steady veiling light. Observers judged that a moving pattern had or had not been presented using the rating scale described earlier. Observers were informed before each block of trials which condition was to be presented.

The results are shown in Figure 5. Sensitivity measures are plotted against various cue reliabilities. The three least reliable cue conditions (360, 300, and 240 degrees) were significantly worse than all other conditions ($p < .05$). The 180 and 120 degree range conditions did not differ significantly from each other, but were significantly worse than the 60 or 0 degree conditions ($p < .05$). Similarly, 60 and 0 degree conditions did not differ from each other but were significantly lower than the certainty condition. Thus as the cue became more and more reliable, sensitivity increased and the detrimental effects of uncertainty declined.

To determine if these results were caused by a variation in criterion --willingness or reluctance to guess that movement had occurred-- B values were also calculated. An analysis of

variance showed no significant change across conditions indicating that the observer's bias for or against saying that had been presented did not vary across conditions.

A very reliable cue delivered 700 msec in advance of the target virtually eliminates the effect of direction uncertainty. More importantly, in order to reduce the effects of direction uncertainty, a cue does not have to specify with perfect accuracy the direction of subsequent movement. A cue that indicated a direction of movement only within a range of 120 degrees was still sufficient to reduce the uncertainty effect by half.

These results have clear implications for reducing uncertainty in non-laboratory situations. If crude but timely cues aid performance, then it will be possible to develop special hardware that could assist human observers by doing a quick, rough analysis of a signal and giving the observer information to reduce his uncertainty about the target. Such a sensory cue, reduced to hardware form, could be useful to pilots, drivers, radar operators, or anyone for whom uncertainty about moving targets is costly. If devices of this kind are to be helpful, however, they must deliver the information in time to allow the observer to assimilate it and adjust his target search accordingly. Feasible sensory aids would not allow the observer much advance warning, so it is essential to know how far in advance this information must be provided to facilitate performance. Furthermore, feasible sensory aids are more likely to provide only crude information rather than specifying stimulus characteristics precisely. But these developments are still in the planning stage.

Let us end with a quite different kind of study of direction uncertainty, one that relates closely to the model presented earlier (Figure 1). In one experiment by Ball, Machamer and Sekuler (unpublished) an observer's ability to identify the direction of motion that he had just seen was tested at various levels of visibility. As we shall see, there were some rather striking discrepancies between detection performance --simply seeing the motion-- and the ability to assess direction of motion. Ball et al. first established the 2-AFC detection levels for a wide range of combinations of target duration and contrast. These data are of interest in their own right, but are not directly relevant here. However, we shall have to cite some of them because they provide reference points for the identification data that are of primary interest.

A moving dot pattern was presented on every trial and the observer judged its direction. Stimuli were drawn randomly from a uniform distribution of directions covering the range from 75 to 105 degrees. A protractor around the display aided the observer in reporting perceived direction. A trial consisted of a variable duration moving pattern following which the observer reported the perceived direction of motion. In a block of trials, each of the 31 possible directions appeared three times in random order.

Ball et al. calculated a)the correlation between the direction actually presented and the observer's judgment, as well as b)the observer's average error in judgment. The average

error was based upon the absolute value of the difference between the actual and perceived directions. Some of these results are shown in Figure 6 where 2-AFC detection performance for each stimulus is indicated by the number above each data point. Significant correlations ($p < .05$) lie above the dotted horizontal line.

First, note identification performance when the random dot display was presented at the highest contrast for the longest durations, 500 msec. Correlations between perceived and actual direction of movement averaged 0.93 and 0.89 for the two observers. So, under optimal conditions observers can report direction of movement with a fair degree of accuracy. The average errors (2-4 degrees) correspond well to direction difference thresholds measured under comparable conditions. At this high contrast observers detected movement 100% of the time with virtually no strain. The middle curve shows identification performance at a lower contrast value -- but one still permitting 100% or near 100% detection. At this contrast, ability to report the direction of movement falls off as duration is shortened. Oddly enough, contrast and duration must be high enough to mediate nearly 100% detection if the observer's judgment of direction is to be better than chance. The results demonstrate that detection of moving dot patterns may sometimes be far easier than judgment of their direction.

These findings were extended in other detection-cum-identification experiments by Ball et al. One of those experiments gives another estimate of the breadth of tuning of directionally-selective mechanisms. The procedure was a 2x2-AFC experiment. Each trial consisted of two intervals; moving dots were presented in one, nothing in the other. The motion that did occur was randomly drawn from pairs of alternative directions. The observer's first task (detection) was to indicate the interval that contained motion. The observer's second task (identification) was to indicate which of the two directions had been presented. Ball et al. compared detection and identification levels for various differences between the two alternative directions. As the difference increased, detection fell and identification improved.

When the difference between directions had reached approximately 150 degrees, the two measures were identical and they remained so for larger differences. The logic of Watson and Robson (1980) suggests that 150 degrees would be the minimum difference between center directions (cf. Figure 1) that that produces no overlap between the two mechanisms whose center directions we are considering. This corresponds to a range of 75 degrees from the center direction of some mechanism to the point at which its sensitivity has declined essentially to zero. As you may notice, this value is consistent with several other estimates of directional selectivity that we have cited earlier. It seems that operations of widely differing kinds converge on approximately this value.

These experiments suggest another point that is quite important from the perspective of this Seminar. Here we mean the discrepancy between ease of seeing a moving stimulus and the possibly severe difficulties in correctly assessing its direc-

tion. Military standards specify the desired visibility for various tasks in terms of detection levels, not in terms of identification levels. The discrepancy between the two measures suggests that since those who create such standards are often really interested in insuring a certain level of identifiability, the standards must be defined in such terms. One cannot guarantee good identifiability simply by arranging conditions to produce good detectability. The two need not go hand in hand.

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FIGURE LEGENDS

Figure 1. A hypothetical set of sensitivity profiles for directionally-selective mechanisms, A-K, arrayed along a portion of the direction continuum. The magnitude of response evoked in any mechanism by some stimulus is represented by the height of the mechanism at the point corresponding to the stimulus direction. Mechanism A is most sensitive to direction a, mechanism B is most sensitive to direction b, and so on. Note however, that mechanism A is also sensitive to movement in directions b, c, d, e, f, and g, though to a reduced degree. Mechanism A is not sensitive to movement in directions h-k, so movement in those directions evokes no response in A.

Figure 2. Three different psychophysical responses to motion as a function of direction. Filled circles represent the duration of motion after-effect elicited by various directions; open squares represent the reaction time to onset of motion in various directions; "x"s represent the contrast threshold for seeing dot patterns that move in various directions. All three measures have been scaled so that their means coincide.

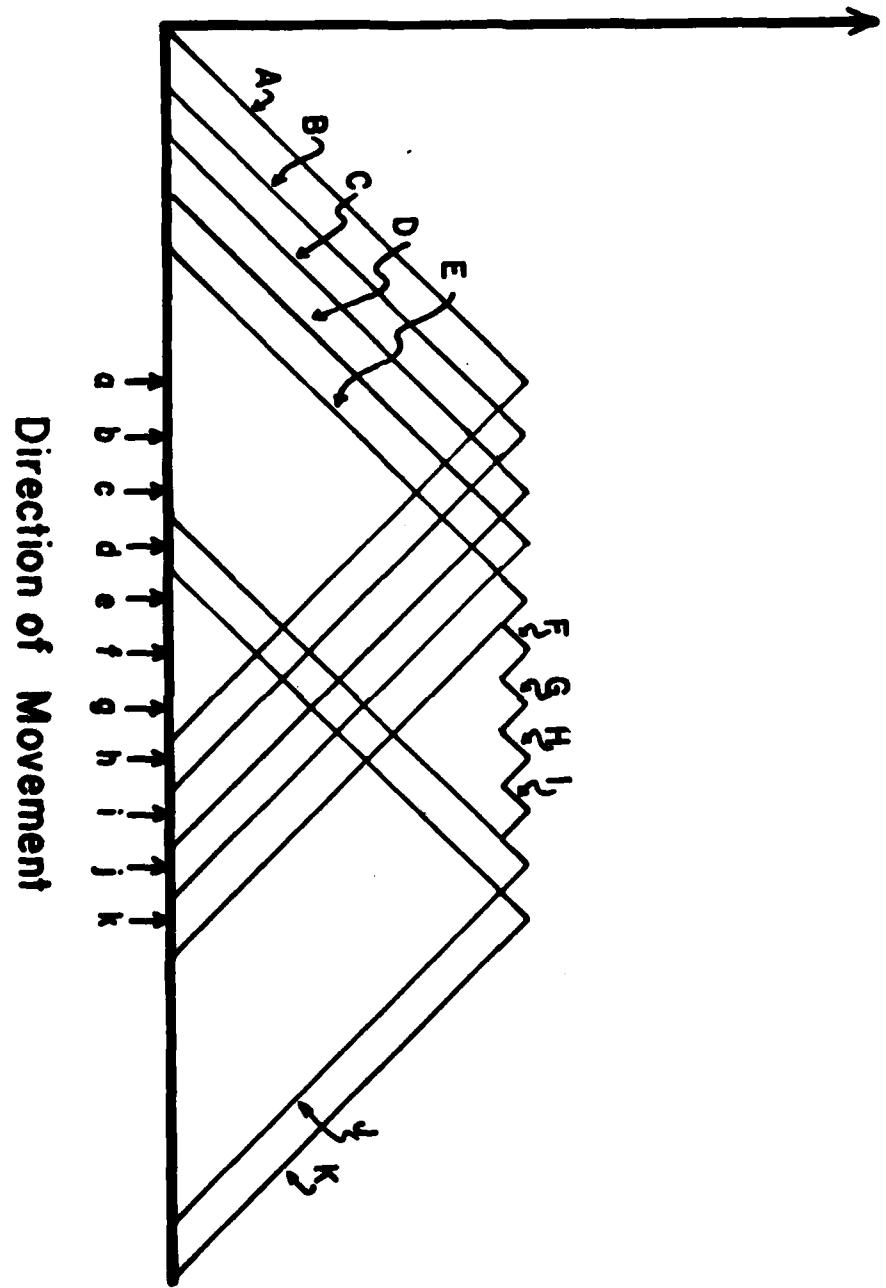
Figure 3. Reaction times to dot patterns moving at various velocities. Left panel shows results using annular stimuli of various diameters right panel shows results with stimuli restricted to central patches. See text for details.

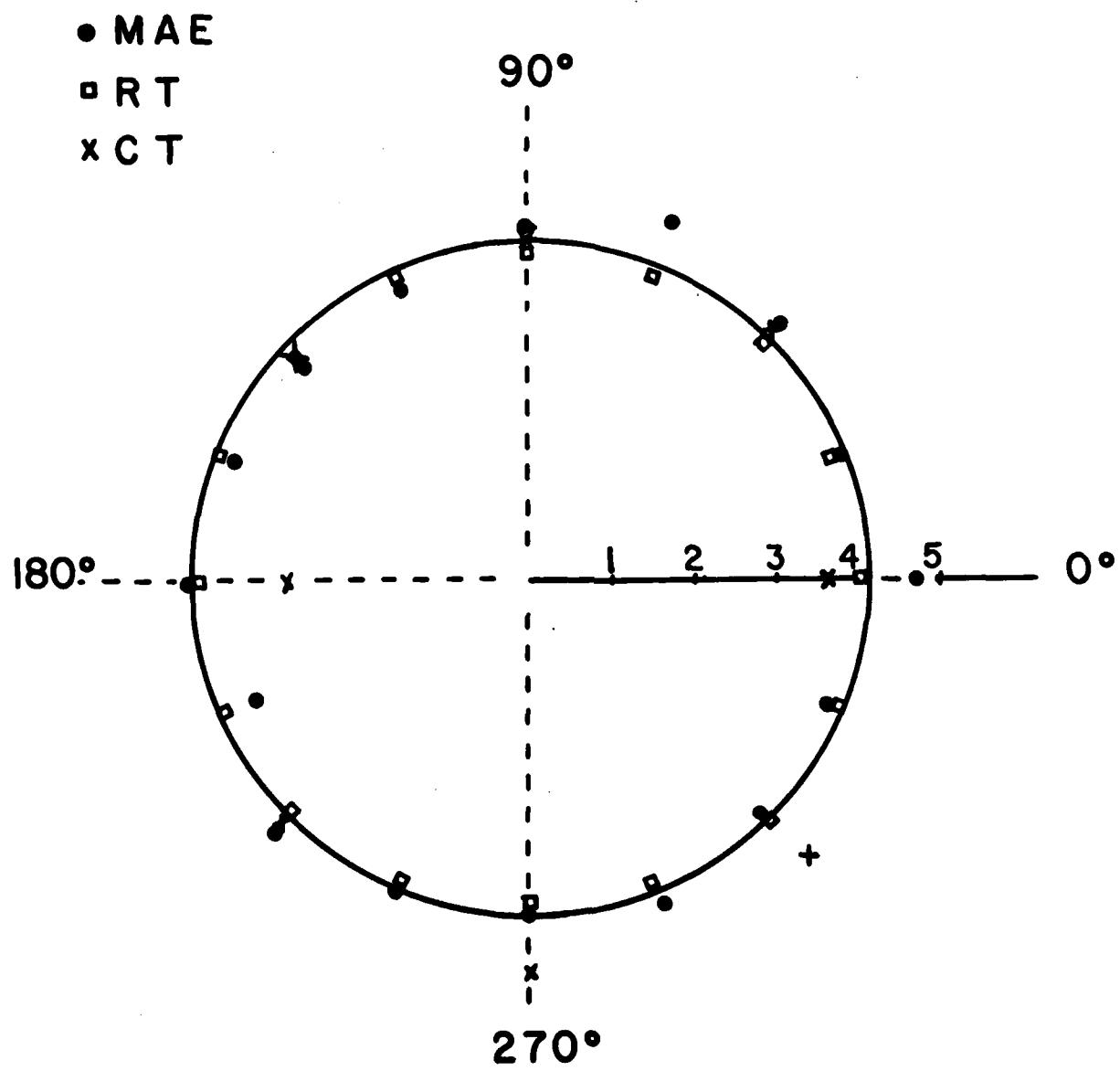
Figure 4. Ratio of perceived to actual speed as a function of target eccentricity. Data are shown for several different target speeds, 0.25, 1, 4, and 16 deg/sec. Missing data are due to apparent standstill at certain combinations of speed and eccentricity.

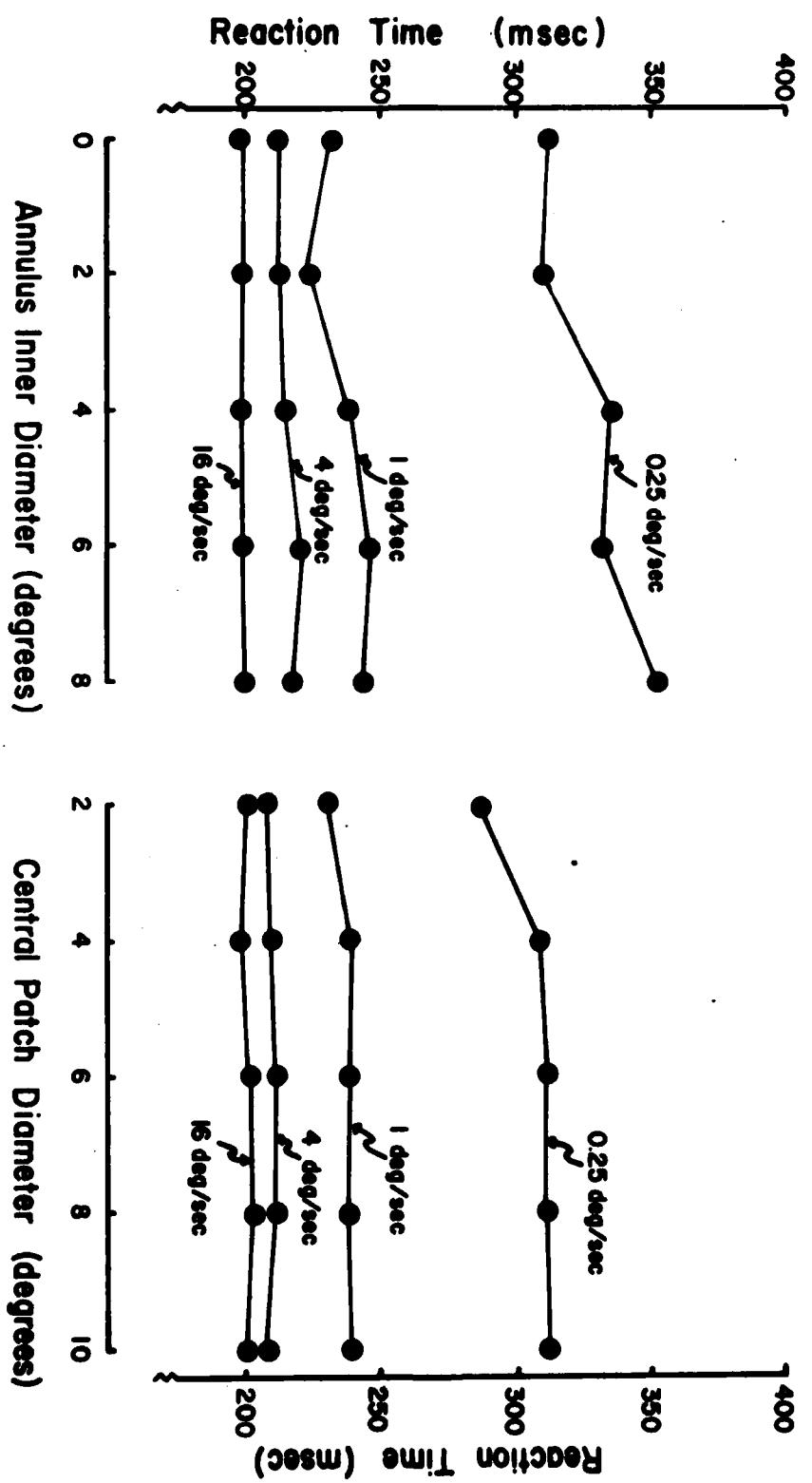
Figure 5. Sensitivity, $zP(A)$, to moving dot patterns. Measurements are shown for three observers. Middle section of x-axis, labelled "range of precision", shows the effect of providing cues, before the motion occurs. The reliability of the cue increases from left to right and the effect of direction uncertainty decreases. Data points at extreme left show performance with complete direction uncertainty and no cue to help the observer. Data points at the extreme right show performance with no direction uncertainty (all patterns move in the same direction).

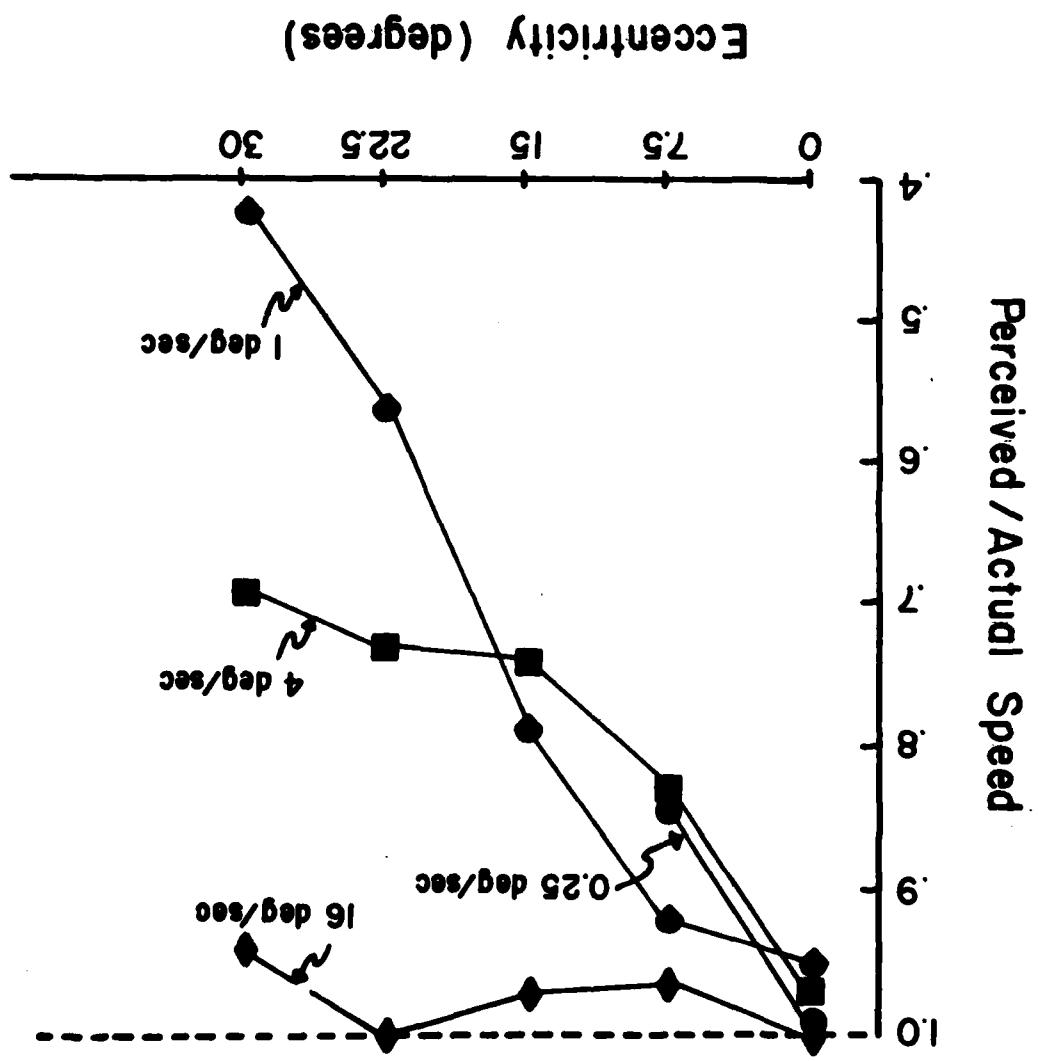
Figure 6. Pearson product moment correlation (r) between reported and actual directions of motion for patterns of various duration. The parameter of the family of curves is the contrast of the dot patterns; numbers above each data point indicate the 2-AFC detection performance for that point. Dashed horizontal line indicates r value at which the correlation between reported and actual directions is significant ($r < .05$).

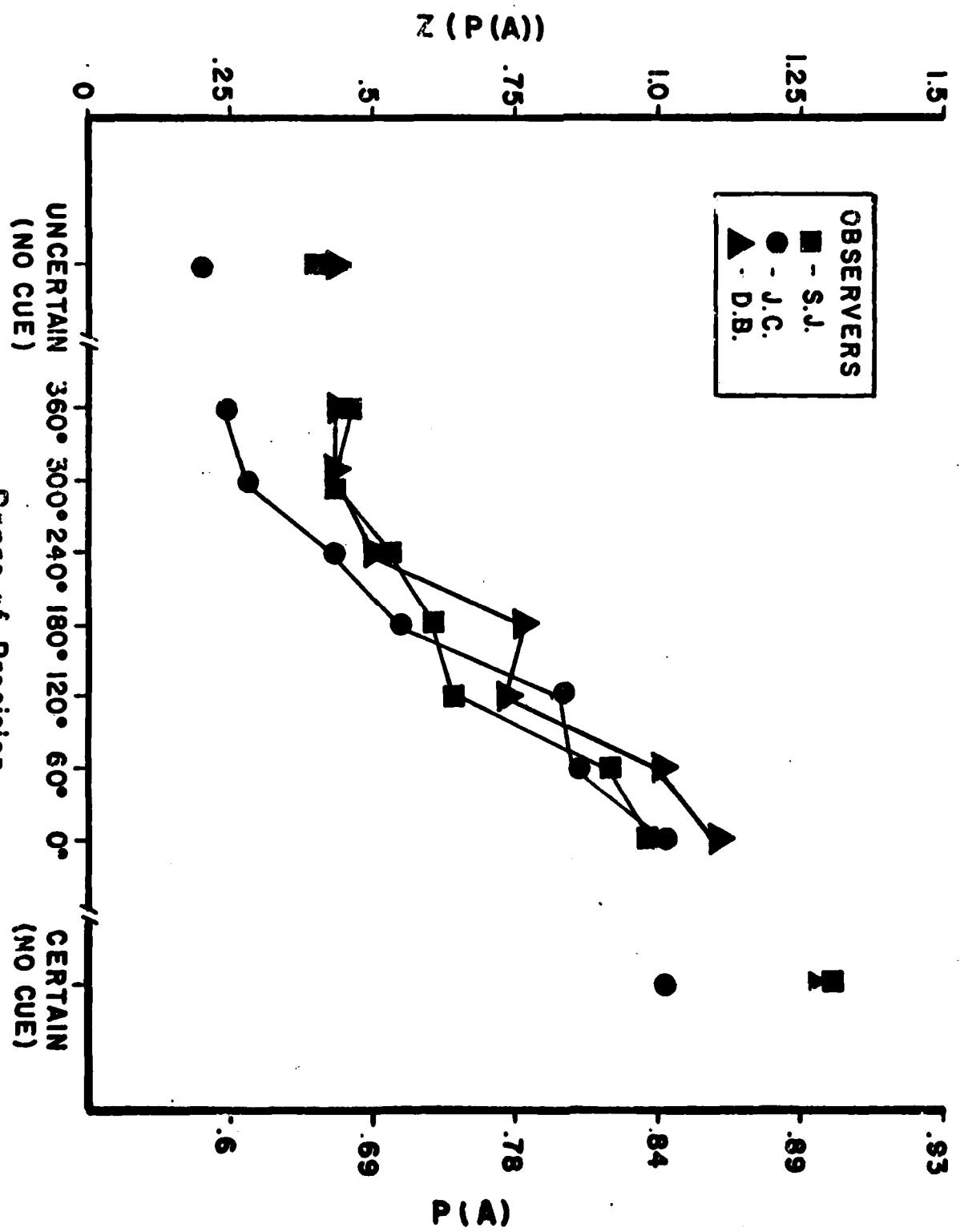
Magnitude of Response











Accuracy of Identification (r)

